Practical Paper

A Generalized Component Substitution Technique for Spatial Enhancement of Multispectral Images Using a Higher Resolution Data Set[1]

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ABSTRACT: A generalized COmponent Substitution (COS) technique is presented for enhancing spatial resolution of multispectral bands using a higher resolution data set. The process involves a simple one-step linear transformation of the combined data space, and the procedure can be used for the implementation of the popular Intensity Hue Saturation (IHS) transformation technique of data merging. In the generalized procedure the weights used in the linear transformation are scene dependent and are determined from multivariate statistical techniques. Examples of enhancement of a SPOT multispectral image and a Landsat TM image of Sydney using a SPOT panchromatic image are presented. The results are compared with that of the IHS technique. The generalized technique may be also used for filtering noise or an unwanted component from a multispectral image.

INTRODUCTION

THE AVAILABILITY OF HIGH RESOLUTION PANCHROMATIC (PA) data in the form of aerial photographs and satellite images has given rise to a host of procedures to spatially enhance coarser resolution multispectral (XS) data for display purposes. These procedures are likely to become more popular with the launching of Landsat-6 in which the Enhanced Thematic Mapper (ETM) sensor will have a 15-m band co-registered with XS bands.

The merging of high resolution images is used to enhance spatial resolution of the XS bands in a variety of combinations. Chavez *et al.* (1984), Cliche *et al.* (1985), and Carper *et al.* (1990) have enhanced the SPOT XS bands of pixel resolution 20m using the PA band of 10-m resolution. Welch (1984) has used the higher resolution SIR-A image to enhance Landsat images. Welch and Ehlers (1987) have merged SPOT PA data with Landsat TM images. High resolution aerial photographs were used for enhancing Landsat TM data by Chavez (1986). Apart from the problem of improving spatial resolution, the merging of multisource images is also used for enhancing feature classes, mainly by using IHS transformation (Harris *et al.*, 1990; Chavez *et al.*, 1984).

In general, the merging processes found in the literature involve computation of new variables as a linear or nonlinear weighted functions of both PA and XS data. Examples of linear functions are pixel-by-pixel addition, subtraction, and principal component techniques presented in Chavez (1986). Non-linear functions are used for data merging by Cliche *et al.* (1985) and Chavez (1986). The weights used in the above procedures are empirical. Clearly, there is a need to formalize the mathematical procedures involved in the merging exercise.

In this study only the problem of enhancing the spatial resolution is addressed. However, the procedure developed can be used for any enhancement technique that involves a forward linear transformation, replacement of a variable in the transformed space, and the inverse transformation. It is desirable that any procedure for merging high resolution panchromatic data with low resolution multispectral data should preserve the original spectral characteristics of the latter as much as possible (Chavez *et al.*, 1991; Carper *et al.*, 1990; Chavez *et al.*, 1984). The procedure should be optimal in the sense that only the additional spatial information available in higher resolution data are imported into multispectral bands. The high pass filter (HPF) procedure, recently demonstrated by Chavez *et al.* (1991) is quite effective in enhancing edges and preserving original multispectral characteristics. However, as alluded to by them, the procedure has limitations in passing on important textural information from a high resolution band to lower resolution multispectral images.

The purpose of the present study is to present a simple and general mathematical procedure for enhancing the spatial resolution of XS bands using a higher resolution image and to provide statistical guidelines for achieving desirable results mentioned above. The procedure, called "COmponent Substitution (COS)," is general in the sense that it can be used for implementing any technique that involves linear transformation.

COMPONENT SUBSTITUTION TECHNIQUE (COS)

The COS technique essentially involves three basic steps as shown in Figure 1. In step 1 (Figure 1a) the multispectral data are linearly transformed or, in a geometric sense, the reference axes are rotated. The purpose of the forward transformation in step 1 is to extract an image from the multispectral data that would closely resemble the higher resolution data. For example, in the IHS technique it is assumed that the intensity image, which represents the brightness variation, closely resembles the higher resolution data. The higher resolution image commonly used is the SPOT panchromatic band covering the visible spectra. In step 2 (Figure 1b) one of the components, to be called the replacement component, in the transformed space is replaced by the higher resolution panchromatic data. In step 3

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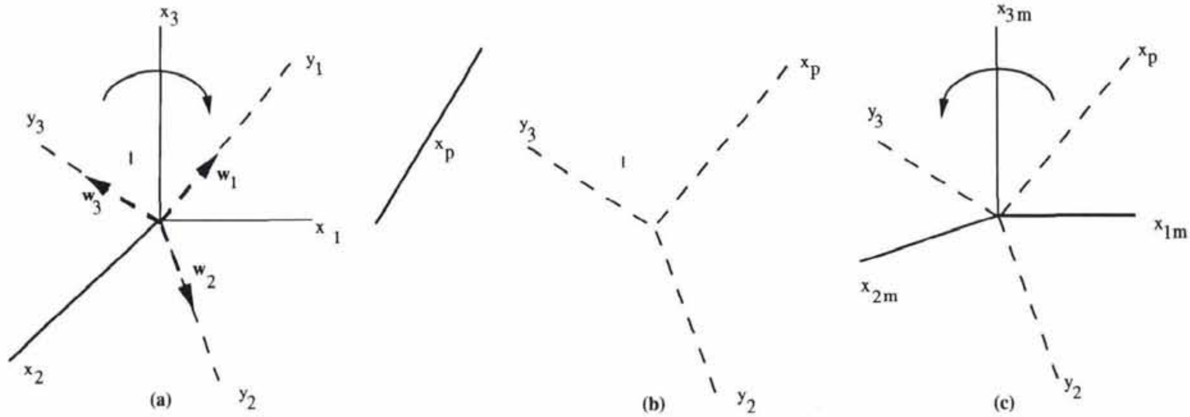


FIG. 1. Geometric view of the COmponent Substitution (COS) Technique. (a) Forward transformation. (b) Replacement of substitution component y_1 by the higher resolution data x_p. (c) Inverse transformation to the original space.

(Figure 1c) the variables are inverse transformed to the original space. In step 1 the user has the option of choosing the type of linear transformation. The simplicity and generality of COS enables the implementation of new procedures as explained later.

By far, the IHS transformation is the most popular technique used for merging higher resolution data with the lower resolution multispectral data to enhance the spatial resolution of the multispectral image display. Intensity, as used in the IHS procedures for merging data (Chavez *et al.*, 1984; Haydn *et al.*, 1982), is a linear transformation of red, green, and blue (RGB) values of a displayed image. It is important to note that the hue and saturation values in IHS space are not linear functions of RGB. However, the IHS values, commonly expressed in cylindrical or spherical coordinates, can be mapped to cartesian coordinates through imaginary values I, ν_1, and ν_2 using a linear transformation as follows (Harrison and Jupp, 1990):

$$\begin{bmatrix} \mathrm{I} \\ \nu_1 \\ \nu_2 \end{bmatrix} = \begin{bmatrix} 1/\sqrt{3} & 1/\sqrt{3} & 1/\sqrt{3} \\ 1/\sqrt{6} & 1/\sqrt{6} & -2/\sqrt{6} \\ 1/\sqrt{2} & -1/\sqrt{2} & 0 \end{bmatrix} \begin{bmatrix} \mathrm{R} \\ \mathrm{G} \\ \mathrm{B} \end{bmatrix} \tag{1}$$

where I is the intensity value and ν_1, ν_2 are imaginary components related to hue (H) and saturation (S) as

$$\mathrm{H} = \tan^{-1}(\nu_2/\nu_1) \tag{2}$$

$$\mathrm{S} = \sqrt{\nu_1^2 + \nu_2^2} \tag{3}$$

The imaginary components may be inverted to RGB values using the relationship

$$\begin{bmatrix} \mathrm{R} \\ \mathrm{G} \\ \mathrm{B} \end{bmatrix} = \begin{bmatrix} 1/\sqrt{3} & 1/\sqrt{6} & 1/\sqrt{2} \\ 1/\sqrt{3} & 1/\sqrt{6} & -1/\sqrt{2} \\ 1/\sqrt{3} & -2/\sqrt{6} & 0 \end{bmatrix} \begin{bmatrix} \mathrm{I} \\ \nu_1 \\ \nu_2 \end{bmatrix} \tag{4}$$

Equation 1 shows that the IHS values of RGB data can be stored as linearly transformed values I, ν_1, ν_2. Any process that needs only the I values in IHS space, such as the IHS technique of data merging, could be implemented through RGB–I$\nu_1\nu_2$ linear transformation. Hence, the COS technique, which deals with only linear transformations, is applicable to the popular IHS technique of data merging for resolution enhancement.

MATHEMATICAL PROCEDURE

Let $\mathbf{x}$ be the vector of dimension $(k+1)$ consisting of k multispectral and 1 higher resolution values for a pixel. The following mathematical procedure is applicable for any k. However, in the present study of data merging for improving displays k is 3 as only three bands are used in color monitors. That is,

$$\mathbf{x}'_{sp} = (\mathbf{x}_s, x_p) \tag{5}$$

where $\mathbf{x}_s$ is the multispectral data vector and x_p is the higher resolution data. $\mathbf{x}_{sp}$ is the combined original data vector

$$\mathbf{x}'_s = (\mathrm{x}_1, \mathrm{x}_2, \mathrm{x}_3, \ldots, \mathrm{x}_k). \tag{6}$$

Let $\mathbf{W}$ be the matrix containing the rotation vectors, shown in Figure 1a, along the columns. Then,

$$\mathbf{W} = (\mathbf{w}_1, \mathbf{w}_2, \mathbf{w}_3, \ldots, \mathbf{w}_k) \tag{7}$$

Vector $\mathbf{w}_1$ determines the linear combination of multispectral bands y_1 in Figure 1a. Vectors $\mathbf{w}_2, \mathbf{w}_3, \ldots, \mathbf{w}_k$ are orthonormal to $\mathbf{w}_1$ and we need not know them. We select $\mathbf{w}_1$ as a replacement vector.

If $\mathbf{y}_s$ is the transformed data vector, we have

$$\mathbf{y}_s = \mathbf{W}'\mathbf{x}_s \tag{8}$$

where

$$\mathbf{y}'_s = (y_1, y_2, y_3, \ldots, y_k). \tag{9}$$

y_1, y_2, and y_3 may be compared to I, ν_1, and ν_2 in Equation 1.

If we replace y_1 by x_p, the vector in Equation 9 will be modified to

$$\mathbf{y}'_m = (x_p, y_2, y_3, \ldots, y_k) \tag{10}$$

$$= (y_1 + \delta y, y_2, \ldots, y_k) \tag{11}$$

$$= (\mathbf{y}_s + \Delta\mathbf{y}_s)' \tag{12}$$

where

$$\Delta\mathbf{y}'_s = (\delta y, 0, 0, \ldots, 0) \tag{13}$$

and

$$\delta y = (x_p - y_1) = x_p - \mathbf{w}'_1\mathbf{x}_s. \tag{14}$$

Inverting back to the original space of Figure 1a, we get a modified higher resolution multispectral data vector

$$\mathbf{x}_m = \mathbf{W}\,\mathbf{y}_m \text{ because } \mathbf{W}^{-1} = \mathbf{W}' \text{ in Equation 8.}$$

$$= \mathbf{W}\,\mathbf{y}_s + \mathbf{W}\,\Delta\mathbf{y}_s$$

$$= \mathbf{x}_s + \delta y\,\mathbf{w}_1$$

$$= \mathbf{x}_s + (x_p - \mathbf{w}'_1\,\mathbf{x}_s)\,\mathbf{w}_1. \tag{15}$$

Equation 15 may be further simplified to

$$\mathbf{x}_m = \mathbf{T}\,\mathbf{x}_{sp} \tag{16}$$

where $\mathbf{T}$ is a k by $(k+1)$ matrix.

The elements of $\mathbf{T}$ are given in terms of the components of vector $\mathbf{w}_1$. That is,

$$t_{ij} = m - w_{i1}\, w_{j1} \text{ for } j \neq (k+1) \quad (17)$$
$$\text{where} \quad m = 0 \text{ if } i \neq j, \quad m = 1 \text{ if } i = j$$
$$t_{ij} = w_{i1} \quad \text{for } j = k + 1 \quad (18)$$

w_{i1} is the ith component of vector $\mathbf{w}_1$.

The vector $\mathbf{x}_m$ in Equation 16 is the required data vector which will have the higher resolution information of the panchromatic band incorporated in it. Notice that the three steps shown in Figure 1 are accomplished in one simple equation (Equation 16). Also note that the process requires knowing only the axis (vector $\mathbf{w}_1$) to be replaced by the higher resolution data.

NEW POSSIBILITIES IN COS

The simplicity of Equation 16 also facilitates the easy testing of various forward transformation techniques in step 1 of Figure 1a. In the present study four possibilities are tested. The procedures are named after the type of forward transformation used and they are

- IHS - Intensity Hue Saturation
- RVS - Regression Variable Substitution
- PCS - Principal Component (PC) Substitution
- SPS - Standardized PC Substitution

INTENSITY HUE SATURATION (IHS) TECHNIQUE

The IHS technique is commonly used for merging high resolution data with low resolution images. Haydn *et al.* (1982) described the technique in great detail and it will not be repeated here. If we choose $\mathbf{w}'_1 = (1/3, 1/3, 1/3)$ or while normalized to unit vector $(1/\sqrt{3}, 1/\sqrt{3}, 1/\sqrt{3})$, y_1 in the forward transformation will be the intensity value in the IHS space; i.e., $\mathbf{x}_m$ in Equation 16 is the output of the IHS technique.

REGRESSION VARIABLE SUBSTITUTION (RVS) TECHNIQUE

One of the challenges we face while merging high resolution data with low resolution multispectral data is to preserve the original spectral characteristics as much as possible. The procedure should be optimal in the sense that only the additional information available in higher resolution data is imported into multispectral bands.

The square of correlation between a variable, derived from a multivariate data set, and a univariate data is a measure of information in the univariate data already explained by the multivariate data. Multiple regression is a tool for deriving a variable, as a linear function of miltivariate data, that will have maximum correlation with the univariate data (Mardia *et al.*, 1979).

In order to preserve the spectral characteristics of multispectral data to the maximum possible extent, it is desirable to find a (linear) combination of multispectral bands that correlates highly with the selected high resolution data. Hence, for the RVS technique, multiple regression is used to determine this linear combination (replacement vector) of multispectral bands, which can be replaced by the panchromatic band. One of the points to consider in this process is that maximization of correlation does not imply the maximization of variance along the combination vector. However, to achieve a noticeable effect after merging, the replacement vector should account for a significant amount of variance or information in the original multivariate set. This point will be explained later with an example.

PRINCIPAL COMPONENT SUBSTITUTION (PCS) TECHNIQUE

In the PCS technique, the principal component transformation is the forward transformation. The PCs are determined using the covariance matrix of multispectral data set. The first PC is replaced by the higher resolution panchromatic data. By replacing the first PC, which accounts for maximum variance in the lower resolution multispectral data, we are maximizing the effect of higher resolution panchromatic data in the merged image. No example for PCS will be presented here as it was found that the standardized PCs are more suitable for the reasons explained below.

STANDARDIZED PRINCIPAL COMPONENT SUBSTITUTION (SPS) TECHNIQUE

The SPS technique is a variation of PCS. The forward transformation is achieved by determining the principal components from the correlation matrix instead of the covariance matrix of multispectral data. The PCs thus determined are called standardized principal components (SPC). Singh and Harrison (1985) have demonstrated some of the advantages of SPCs over PCs. In the correlation matrix the variances of all bands are scaled to unity, making them equally important. In this study it was noticed that the variance of infrared band (band 3) of SPOT image is particularly dominant as shown in Table 1, which is not desirable. The SPS technique was found to give better results compared to the PCS in all merging experiments in the present study.

RESULTS AND DISCUSSION

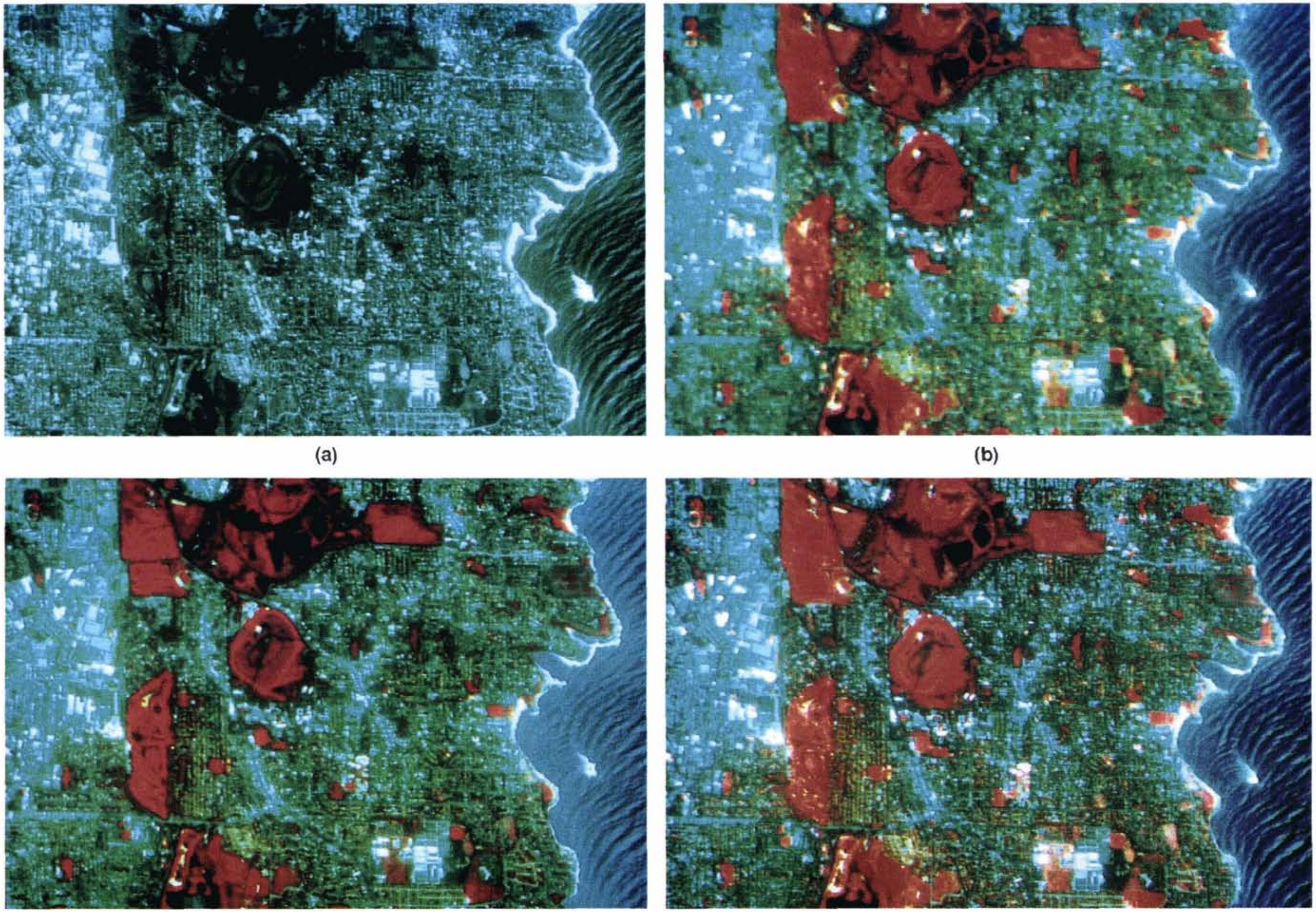
The above techniques were tested on a SPOT (level 1B) image of Sydney, Australia and on a Landsat TM image of a smaller area north of Sydney. In Plate 1 the results of IHS, RVS, and SPS procedures on a SPOT image are shown with the original panchromatic image and the lower resolution multispectral image. In Plate 2, the results of enhancement of a TM image (bands 4, 5, and 7) are shown. The two cases considered here have different characteristics that are useful for revealing the applications and limitations of various processes. The multispectral SPOT image as a whole has a very high correlation with the panchromatic band while the TM image has a very low correlation with the panchromatic band (Tables 3 and 4).

In Tables 1 and 2, the covariance and correlation matrices of the SPOT image of Plate 1b are given. Notice that the correlation between the infrared band and the panchromatic band (Plate 1a) is negligible. Table 3 presents the intensity axis which accounts for 42 percent of the variance in the multispectral bands, while that axis has a correlation of 0.66 with the panchromatic axis. In contrast, the regression axis accounts for 27 percent of the variance in the multispectral space and has a correlation of 0.88 with the panchromatic data.

The effect of high correlation between the regression variable and the panchromatic data is clear in Plates 1c and 1d. The color characteristics in the RVS merged image in Plate 1d closely resembles the original image in Plate 1b. The color resemblance is much better than that achieved by the IHS enhanced image in Plate 1c. This point is further demonstrated in Figure 2 in which the chromaticities (CIE uniform chromaticity scale 1976) of three samples from the slides of images in Plates 1b (original), 1c (IHS enhanced), and 1d (RVS enhanced), taken from the color monitor, are shown. The three samples are taken from three homogeneous areas, which are the same for all the three images, and basically have reddish, greenish, and bluish hues. In the reddish and greenish samples the chromaticity of RVS en-

TABLE 1. COVARIANCE MATRIX OF SPOT IMAGES

	XS1	XS2	XS3	PA
XS1	138.8			
XS2	120.6	133.4		
XS3	1.5	−27.7	416.0	
PA	145.7	152.0	−4.2	229.0



(a) (b) (c) (d)

PLATE 1. Merging of higher resolution SPOT panchromatic data with SPOT multispectral image. (a) Panchromatic image of Sydney, 10-m resolution. (b) Multispectral SPOT image of Sydney of resolution 20 m. Bands 3, 2, 1 in red, green, and blue colors. (c) IHS merged multispectral image shown in b. (d) RVS merged multispectral image shown in b. The apparent resolution of c and d is 10 m. Notice that the color reproduction in d is much closer to the original in b than that in c. The difference is particularly noticeable in various shades of red that distinguish variations in grass and tree covers. (Original data copyright 1986 CNES.)

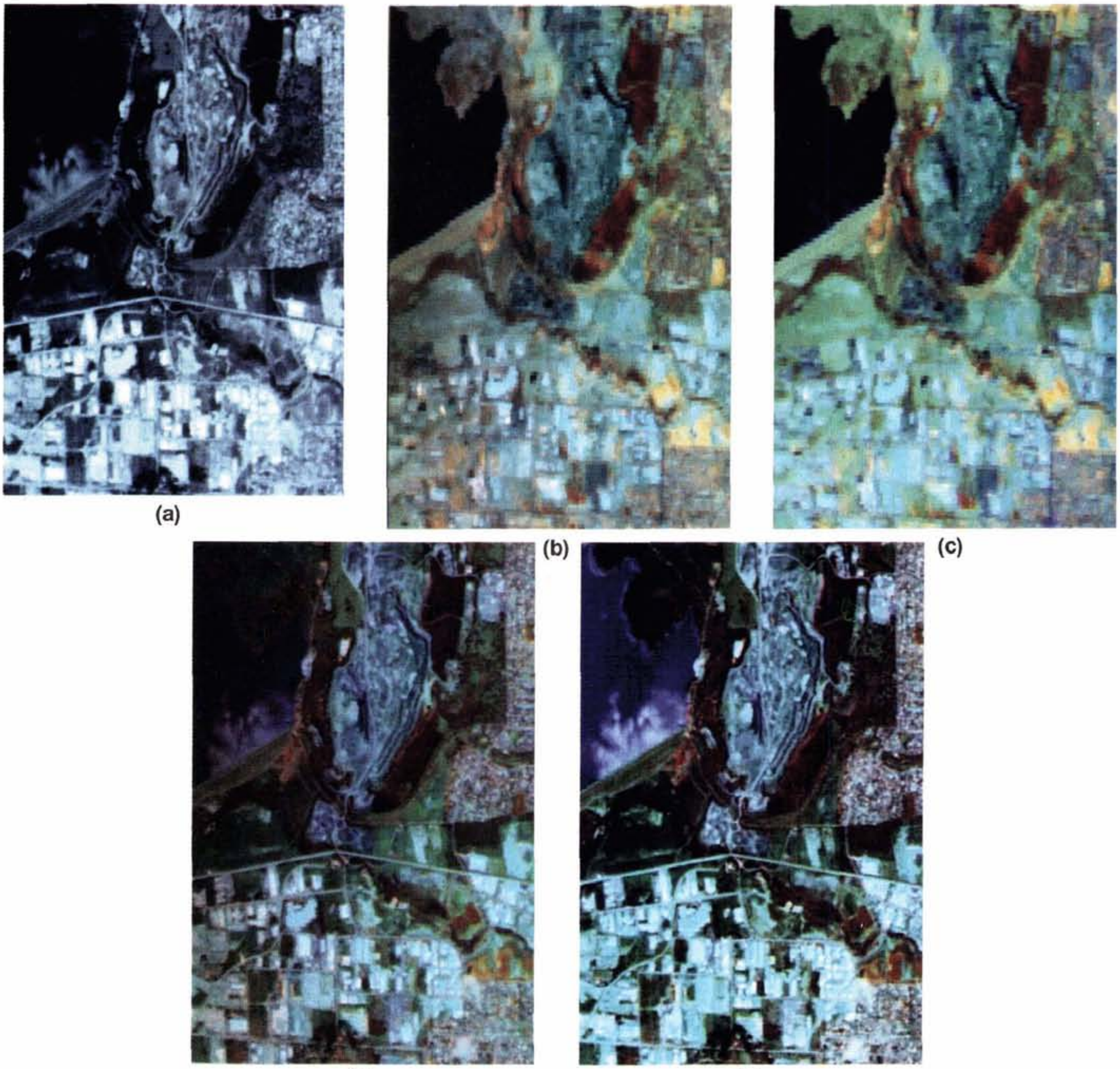


PLATE 2. Merging of higher resolution SPOT panchromatic data with Landsat TM images of bands 4, 5, and 7. (a) SPOT panchromatic image of resolution 10 m. (b) Landsat TM image of the same area. Bands 4, 5, and 7 are in red, green, and blue colors. (c) RVS enhanced image. Notice that no significant resolution improvement has occurred. This is attributed to very low variance accounted by the regression variable in the multispectral space. The color characteristics resemble that of the original image b very well. (d) IHS enhanced image of b. There is significant improvement in resolution. However, the color characteristics of the image are drastically different from those of the original. (e) SPS enhanced image of b. There is marginal improvement in the apparent resolution compared to the IHS enhanced image. However, like in d the color characteristics are different from the original in b. (SPOT data copyright 1986 CNES.)

hanced samples is much closer to the original than the IHS enhanced samples. The chromaticities of bluish samples in both the RVS enhanced and IHS enhanced samples are close to the original. Although the color reproduction in the RVS enhanced image is closer to the original, it is important to note that the urban features like roads and buildings look sharper in the IHS enhanced image.

In Plate 2 the results of enhancement of a TM image of bands 4, 5, and 7 are shown. The statistics relevant to the substitution component are available in Table 4. The image from the RVS technique in Plate 2c closely resembles the original in Plate 2b in color characteristics. However, there is little improvement in the resolution. This is due to the small percentage of variance (3.3 percent) accounted for by the regression variable.

In contrast the images from the IHS and SPS techniques (Plates 2d and 2e) have much improved resolution. The improvement is attributed to the higher percentage of variance accounted by the intensity and the standardized PC axes as shown in Table 4. However, the color composition in both the cases is drastically different from that of the original. The poor color repro-

TABLE 2. CORRELATION MATRIX OF SPOT IMAGES

	XS1	XS2	XS3	PA
XS1	1.000			
XS2	0.886	1.000		
XS3	0.004	−0.117	1.000	
PA	0.816	0.869	−0.013	1.000

TABLE 3. STATISTICS OF SUBSTITUTION COMPONENT AXES (ENHANCEMENT OF SPOT IMAGE OF SYDNEY)

Intensity Axis (IHS technique)		Regression Axis (RVS technique)
	normalized vector coefficients	
(0.577,0.577,0.577)		(0.238,0.970,0.054)
	variance accounted for in XS space	
42.0%		27.0%
	correlation with the panchromatic data	
0.660		0.880

TABLE 4. STATISTICS OF SUBSTITUTION COMPONENT AXES (ENHANCEMENT OF LANDSAT TM IMAGE OF SYDNEY)

Intensity Axis (IHS technique)	Regression Axis (RVS technique)	Standardized PC (SPS technique)
	normalized vector coefficients	
(0.577,0.577,0.577)	(−0.125,0.349,0.929)	(0.527,0.629,0.582)
	variance accounted for in XS space	
82.9%	3.3%	85.1%
	correlation with the panchromatic data	
0.498	0.657	0.499

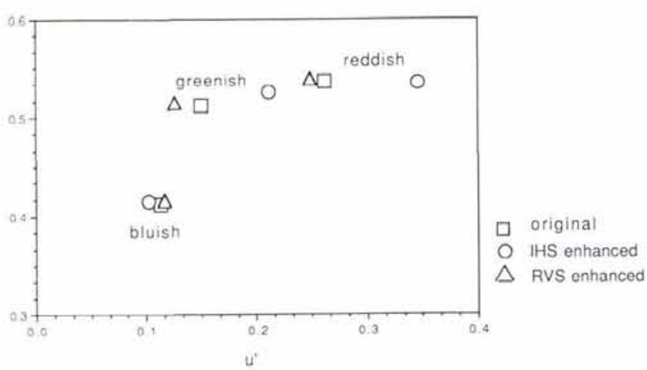


FIG. 2. The chromaticities (CIE uniform chromaticity scale 1976) of three samples from the slides of images in Plates 1b (original), 1c (IHS enhanced), and 1d (RVS enhanced), taken from the color monitor, are shown. The three samples are taken from three homogeneous areas, which are same for all the three images, that have basically reddish, greenish, and bluish hues. In reddish and greenish samples the chromaticity of RVS enhanced samples is much closer to the original than the IHS enhanced samples. The chromaticities of bluish samples in both the RVS enhanced and IHS enhanced samples are close to the original.

duction is due to the low correlation of the above axes with the higher resolution data. The resolution improvement from the SPS technique is much better than that obtained from the IHS technique. This is expected as both the correlation with the panchromatic band and the variance of the first standardized PC (Table 4) are higher than those for the intensity axis in the IHS technique.

The COS technique can also be used as an efficient tool for filtering noise in multispectral images. The technique has been used to filter out haziness in a Landsat MSS image of a bushfire. Principal component 3 of the four-band data set contained most of the haze condition. The image (not shown) was reconstructed by replacing the pixel values in principal component 3 in step 2 (Figure 1b) by the mean of the component. A similar approach may be used for filtering out noise from multispectral images if a component containing noise can be determined. For example, the maximum noise fraction (MNF) technique (Green *et al.*, 1988) may be used for identifying such a component.

CONCLUSIONS

A simple linear relationship for the COmponent Substitution (COS) procedure facilitates the easy substitution of higher resolution data for regression variable in RVS, intensity in IHS, a principal component in PCS, and a standardized principal component in SPS techniques. Time may be saved by selecting a proper merging technique, from the suite of possibilities suggested above.

Regression Variable Substitution (RVS) provides the best result from the point of view of reproducing the original spectral characteristics. The resolution enhancement, however, depends on other factors listed below.

The essential ingredients for achieving best results from the COS technique are (1) high correlation between the replacement component and the higher resolution data (RVS is best suited for achieving this aspect), (2) high percentage of variance accounted by the replacement component (the SPS or PCS technique is best suited for this purpose), and (3) equal contribution from each multispectral band in the substitution component (the IHS technique best satisfies this condition). To achieve the best result in data merging, a replacement component must be selected that best satisfies all the three criteria.

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